WACCM and WACCM/CARMA studies at CU LASP: March 2009 Update

Michael Mills, Cora Randall, Brian Toon, Lynn Harvey, Xiaohua Fang, Bodil Karlsson, Matthias Brakebusch, Susanne Benze, Jeff France, Donavan Wheeler, Laura Holt, Jason English, Eric Wolf

Charles Bardeen, Dan Marsh, Rolando Garcia, Doug Kinnison, Aimee Merkel, Simone Tilmes, Francis Vitt
CU LASP’s WACCM Activities Spanning the atmosphere

Mesosphere

Comparisons to observed O3, H2O, Temperature
Sulfate aerosol modeling

Cold-air outbreaks

PMCs

Stratopause / vortex dynamics

Figure adapted from Canadian Space Agency

Spanning the atmosphere
WACCM, CAM & CARMA at LASP

Talk outline:

- **WACCM**
  - compared to meteorological data
    - Polar vortex dynamics & sudden stratospheric warmings
    - Cold air outbreaks
  - compared to satellite data
    - SABER & MLS: Stratopause T & Z
    - MLS O3, N2O, H2O & T
  - Energetic particle precipitation
  - Parameterized PMCs
    - Interhemispheric coupling

- **WACCM/CARMA**
  - Sulfate nucleation
  - PMCs, meteoritic dust
  - Mesospheric sulfate

Additional ongoing Toon group studies:

- **WACCM/CARMA**
  - Early Earth hazes

- **CAM/CARMA**
  - Tropospheric dust
  - Sea salt
  - Titan
  - Mars
  - Subvisible cirrus
WACCM compared to meteorological data

Polar vortex dynamics & sudden stratospheric warmings (L. Harvey)
Cold-air outbreaks (D. Wheeler)
Zonal Mean Vortex and Anticyclone Frequencies

January

July
WACCM Simulation of Strat Warming is Reasonable

Courtesy of L. Harvey
10 hPa Strat Warming Diagnostics

WACCM3
15 years,
MetO 1991-2008,
GEOS-5 2004-08

WACCM simulates fewer major and minor warmings than the analyses, except in April (final warming).

Courtesy of L. Harvey
WACCM and ERA-40 Cold-Air Outbreaks

ERA-40 Surface Temperature

WACCM 1000 hPa Temperature

ERA40 12Z Surface

WACCM ~1000mb

1995-96

Year 15

Courtesy of D. Wheeler
Cold-Air Outbreak Climatology

ERA40 12Z Surface

45 years

WACCM ~1000mb

30 years

0.000 0.003 0.005 0.008 0.011 0.014 0.016 0.019 0.022 0.024 0.027
(# of Points)/(# of Longitude Points) per 30 years

Courtesy of D. Wheeler
WACCM compared to satellite data

SABER & MLS: Stratopause T & Z (J. France, L. Holt)
MLS O$_3$, N$_2$O, H$_2$O & T (M. Brakebusch, S. Benze)
WACCM, GEOS, SABER, and MLS
Stratopause Temperature and Height

MLS T Feb 2006

SABER

GEOS-4

WACCM

Stratopause Temperature 70N

Stratopause Height 70N

Courtesy of J. France and L. Holt
WACCM stratopause is warmer inside the vortex, cooler outside.
WACCM stratopause is lower except at the vortex edge.
SD-WACCM vs. MLS O$_3$ & N$_2$O

Color contours: O$_3$
Black contours: N$_2$O

Courtesy of M. Brakebusch
SD-WACCM vs. MLS: H$_2$O

H$_2$O (ppmv)

70°S

70°N

Courtesy of S. Benze
SD-WACCM vs. MLS: Temperature

Temperature (K)

70°S

70°N

Courtesy of S. Benze
Energetic particle precipitation

- Ionization: $N_2 \rightarrow NO_x$

- Auroral electrons
  - 1 - 30 kev

- Add medium-energy electrons (MEE)
  - 30 kev - 2.5 Mev

Figure from Fang et al., JGR, 2008.
NO$_x$ descent with medium-energy electron precipitation

MIPAS, Antarctic Winter 2003

WACCM with MEPED activity level 1

Courtesy of C. Randall
Medium-energy electrons induce $O_3$ depletion

Courtesy of C. Randall
Parameterized Polar Mesospheric Clouds in WACCM

Interhemispheric coupling in WACCM (B. Karlsson)
Interhemispheric Coupling

Observed PMC radius (OSIRIS) vs. winter stratospheric temperature (ECMWF)

Correlation coefficient: -0.93

Temperatures averaged 60-90°, 10-100 hPa

Correlation coefficient: -0.84

Correlation coefficient: -0.61

Karlsson et al., 2007; Körnich et al. submitted to ASR

Courtesy of B. Karlsson
WACCM/CARMA

Sulfate nucleation at the tropopause (J. English)
PMCs with dust nuclei (C. Bardeen)
Mesospheric sulfate as PMC nuclei (M. Mills)
Early Earth haze (E. Wolf)
**Sulfate nucleation schemes**

Observations: Brock et al., 1995

Binary homogeneous nucleation calculation (Zhao) compared to LUTs for BHN and for ion-mediated nucleation (Yu)

Simulated Number Concentrations

Courtesy of J. English
Meteoritic Dust as PMC Nuclei

Dust concentrations highly sensitive to gravity wave tuning.

Courtesy of C. Bardeen
WACCM/CARMA PMC statistics compared to SOFIE observations

Summary

<table>
<thead>
<tr>
<th></th>
<th>SOFIE v1.01</th>
<th>WACCM/CARMA</th>
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<tbody>
<tr>
<td>Events</td>
<td>1432</td>
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<td>Clouds</td>
<td>1130</td>
<td>959</td>
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<td>Zmax &lt; 79 km</td>
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Seasonal Mean

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<th>Units</th>
<th>SOFIE</th>
<th>WACCM</th>
<th>Difference</th>
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<td>Height</td>
<td>km</td>
<td>83.53</td>
<td>83.26</td>
<td>-0.27 km</td>
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<tr>
<td>Base</td>
<td>km</td>
<td>80.16</td>
<td>80.78</td>
<td>0.62 km</td>
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<td>Top</td>
<td>km</td>
<td>87.01</td>
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<td>Thickness</td>
<td>km</td>
<td>6.85</td>
<td>6.92</td>
<td>0.96%</td>
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<tr>
<td>Column IWC</td>
<td>ug m⁻²</td>
<td>36.65</td>
<td>30.32</td>
<td>-17.26%</td>
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<tr>
<td>B(3.064)</td>
<td>km⁻¹</td>
<td>4.36E⁻⁵</td>
<td>4.54E⁻⁵</td>
<td>4.18%</td>
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<tr>
<td>Re</td>
<td>nm</td>
<td>35.68</td>
<td>42.43</td>
<td>18.91%</td>
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<tr>
<td>Mass</td>
<td>ng m⁻³</td>
<td>13.45</td>
<td>13.68</td>
<td>1.69%</td>
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<tr>
<td>Number</td>
<td>cm⁻³</td>
<td>406.68</td>
<td>75.95</td>
<td>-81.33%</td>
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<tr>
<td>Water Vapor</td>
<td>ppmv</td>
<td>4.35</td>
<td>4.90</td>
<td>12.53%</td>
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</table>

Courtesy of C. Bardeen
Sulfate as PMC nuclei

Hundreds to thousands per cm$^3$ available nuclei
Mesospheric sulfate seasonality

Sulfates on dust

Pure sulfates

70°N

70°S
WACCM4/CARMA

• Better WACCM integration
  • Supports Open/MP and Hybrid Modes
  • Handles Restarts Properly
  • Integrated with Radiation Code (RRTMG)

• New Version of CARMA
  • Fortran 90
  • Thread Safe
  • Globally Adjusted Kernels & Coefficients
  • Improved Substepping (No Crashing)

Courtesy of C. Bardeen
WACCM, CAM & CARMA at LASP

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• CAM/CARMA
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  ‣ Sea salt
  ‣ Titan
  ‣ Mars
  ‣ Subvisible cirrus
Timeline of included instruments and availability of species. Currently operating instruments are MAESTRO, ACE-FTS, and SOFIE.

Solar Occultation Database

10 satellite instruments

Currently operating: MAESTRO, ACE-FTS & SOFIE

Courtesy of M. Brakebusch
A Titan-like organic haze layer covered the young Earth.

**RESULTS:**
Thicker hazes will cause anti-greenhouse cooling.
• UV shielding minimal

**FUTURE QUESTIONS:**
• How will fractal particles alter haze properties?
• How do organic hazes affect solutions to the Faint Young Sun problem?

**UV and VIS absorption optical depths for Early Earth hazes for various production rates.**

<table>
<thead>
<tr>
<th>Haze production rate (g yr$^{-1}$)</th>
<th>$10^{12}$</th>
<th>$10^{13}$</th>
<th>$10^{14}$</th>
<th>$10^{15}$</th>
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<tbody>
<tr>
<td>$\tau_{uv}$</td>
<td>0.026</td>
<td>0.112</td>
<td>0.47</td>
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<td>$\tau_{vis}$</td>
<td>0.005</td>
<td>0.04</td>
<td>0.249</td>
<td>1.63</td>
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<tr>
<td>$\tau_{uv}/\tau_{vis}$</td>
<td>4.79</td>
<td>2.78</td>
<td>1.89</td>
<td>1.42</td>
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Zonal Mean Vortex and Anticyclone Frequencies

**Jan**

- **WACCM**
- **GEOS-5**

Polar vortex (red) and anticyclone (blue) zonal mean frequency.

- **NH winter anticyclone** in WACCM too weak.
- **NH vortex** too strong.

**Jul**

- **WACCM**
- **GEOS-5**

**SH winter anticyclone** in WACCM too strong in stratosphere and too weak in mesosphere.

- **SH vortex** too weak in stratosphere and too strong in mesosphere.

Courtesy of L. Harvey
Randall et al. (AGU 2007): On average, auroral precipitation causes $>10\%$ increases in NO$_x$ down to $\sim 35$ km in SH
Aurora + MEE

Difference (ppbv)

MEE increases NO\textsubscript{x} > 25% down to 20 km

Courtesy of Cora Randall
Reduced Dust At Summer Mesopause

Bardeen et al. (JGR, 2008)
Polar Mesopause Temperatures

WACCM vs. Lubken [1999], 70°N

Lubken [1999], Tmin=129.00

New, Tmin=127.25

Default, Tmin=127.07

Contour from 120 to 260 by 10

Contour from 120 to 260 by 10

Contour from 120 to 260 by 10

K

120 140 160 180 200 220 240 260

Courtesy of Chuck Bardeen
How Does WACCM/CARMA Compare To SOFIE on AIM?

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<td>0</td>
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Zonal average sulfate concentration (r>1 nm) [# cm$^{-3}$]

>1000 cm$^{-3}$

May 31

Dust sulfate

July 17

90°N
Sulfate Geoengineering
(Rich Turco, 1997)

50 Tg S/y \rightarrow 100 Tg OCS/y \sim 80\% \text{ loss in troposphere}

20\% \rightarrow 20 \text{Tg SO}_2/\text{y}

cooling: several °C

Tropospheric OCS \times 300 \sim 170 \text{ ppbv}
Changes in Monthly-Averaged Global Ozone From 1979-2001

% Change Column O$_3$ from 1979 monthly average

Source: TOMS (NASA) via Mark Jacobson, *Atmospheric Pollution*
Effective radius ($\mu m$)

March Zonal Average

Background

Geoengineered